

Experimental systematic uncertainties (and object reconstruction) on top physics, their correlations, comparison ATLAS vs CMS (vs Tevatron) and common agreements

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Abstract. The experimental systematic uncertainties associated to the reconstruction and calibration of the objects appearing in top quark final states at the LHC and Tevatron are discussed. The strategies followed in the ATLAS and CMS experiments are compared in detail for the cases of the jet energy scale and b -tagging calibrations, where a categorisation of the associated uncertainty sources as well as the corresponding correlations across experiments has been proposed. The estimate of the non-prompt and fake lepton background to the top quark leptonic channels is also discussed.

1. Introduction

The precision of several top quark physics measurements is being improved by combining the results obtained by different experiments of the LHC and Tevatron accelerators. As an example, an LHC [1], Tevatron [2] and even a world average [3] combination of the top quark mass have recently become available. When performing these combinations it is essential to understand the proper categorisation of systematic uncertainties as well as the correlations across experiments for each category. This includes the experimental uncertainties associated to the reconstruction and calibration of the objects appearing in the top quark final state under consideration: jets as well as b -jets and for the leptonic decays channels also leptons and missing transverse energy.

A detailed study has recently been done at the LHC for the jet energy scale and b -tagging calibration uncertainties, resulting in a proposal for the treatment of these uncertainties when performing combinations of measurements provided by the ATLAS [4] and CMS [5] experiments. These uncertainties are the dominant experimental systematic uncertainties in most top quark measurements and will be therefore discussed in more detail in this note.

At the LHC experiments, recent significant improvements on alignment, calibrations and material description in simulations have led to a better understanding of leptons [6, 7, 8, 9, 10]. Uncertainties on the lepton efficiency data/MC scale factors, scale and resolution calibrations are considered in top quark measurements. For what concerns the missing transverse energy performance, the main focus has been put in developing techniques to cope with the high pile-up

activity in the 2012 data [11, 12]. The related uncertainties come from the scale and resolution uncertainties of the reconstructed objects used in the missing transverse energy reconstruction, as well as from the description of the energy not associated to such objects.

In the top quark leptonic final states, after the top quark event selection which includes the identification of isolated leptons, there is still a contribution from non-prompt leptons and other particles (as jets) which are mis-identified as leptons. The most commonly used data driven techniques to estimate the contribution of this background have recently been documented in a dedicated note by the ATLAS Collaboration [13] and will also be summarised here.

2. Jets

A different jet reconstruction algorithm is used in each experiment: Cone algorithms are used at CDF and D0 experiments [14, 15], including midpoints in the list of seeds for the case of D0, and with different cone sizes of 0.4 (0.5) at CDF (D0). At the LHC, the more recent anti- k_t algorithm [16] is used instead with a cone size of 0.4 for the case of ATLAS and 0.5 for CMS.

Jets are reconstructed from calorimeter energy deposits in all experiments except for the case of CMS where particle flow candidates [17] are used as input (excluding those charged hadrons associated with a pile-up vertex). For the purpose of calibration, the jet algorithm is also run on simulated stable particles, excluding those that do not leave a visible energy in the detector (neutrinos), and for the case of ATLAS excluding also muons.

Jet quality criteria as well as pile-up rejection cuts are applied within the different top quark analyses on the calibrated jets. Uncertainties associated to the jet energy scale calibration, resolution and efficiency are considered in these analyses.

The jet calibration at the LHC is designed in order to restore the jet energy to that of jets from stable particles as described above (so-called truth jets). The procedure contains three main steps which are common in ATLAS and CMS [18, 19, 20]:

- **Pile-up correction:** The energy in the jet coming from pile-up is estimated and then subtracted. In the ATLAS experiment, for data collected in 2011 at $\sqrt{s} = 7$ TeV, this offset is estimated based on Monte Carlo (MC) simulations, having the offset proportional to quantities related with both in-time and out-of-time pile-up. With the increase of the pile-up activity in 2012, an improved technique is used: the jet area correction method [19] in which the pile-up contribution is estimated on an event by event basis, with an additional residual correction to obtain an average response insensitive to pile-up across the full η range. CMS uses for all data periods the so-called hybrid jet area technique [20]. The main differences with respect to the ATLAS jet area technique are that it takes care of not subtracting the underlying event contribution and that it only corrects for in-time pile-up, covering the smaller out-of-time effects with an uncertainty.
- **Response correction:** This correction is based on simulation and corrects the energy of the reconstructed jets such that it is equal on average to the energy of the generated MC particle jets. The correction is computed for different bins in p_T and η as the inverse of the jet response. In both ATLAS and CMS, it is estimated using isolated jets from an inclusive jet MC sample generated with Pythia. As mentioned before, the definition of truth jets is not exactly the same due to the fact that in ATLAS muons are not considered. However, this has been checked to have a negligible effect.
- **Residual in-situ correction:** In-situ techniques are used to correct for the remaining differences between data and MC in the jet response. This correction is only applied to data. Several techniques have been used exploiting the p_T balance between a well measured object (like a photon or a Z boson) and the jet to be calibrated. A relative calibration is first performed to equalise the jet response in the forward region to that of the central region using events with only two jets at high p_T . Central jets are then calibrated using Z +jets

(with Z decaying to e^+e^- or $\mu^+\mu^-$) and γ +jets events in the so-called absolute calibration step. To extend the p_T range reached by these samples, ATLAS uses multi-jet events in which a system of now well calibrated low p_T jets recoils against a high p_T jet. The assumed balanced between the reference object and the probe jet used in these in-situ techniques, can be affected by physics effects as additional radiation. The CMS strategy is always to extrapolate to the case of no parton radiation, while ATLAS accounts for this effect only in the uncertainty. The results obtained by the different techniques on the data/MC response ratios are then combined.

Since the jet response depends on the jet flavour, an additional flavour uncertainty is needed for topologies with different jet flavour composition than those used to derive the calibration, as top quark events. This uncertainty takes into account how well the flavour response differences are known by comparing the predictions from Pythia and Herwig++ MC generators.

Uncertainties associated to b -jets are in particular important for some top quark measurements. The ATLAS strategy is to estimate this uncertainty by comparing MC samples with different b fragmentations and B -hadron decays, and cross checking the results obtained using data. CMS, for the case of 2011 data, accounts for this uncertainty in the jet flavour uncertainty (which is evaluated as the maximum difference of all jet responses). For 2012 data, a specific flavour uncertainty is evaluated for each jet flavour. This leads to an uncertainty of 0.5% for the case of b -jets (to be compared to 1-2% uncertainty obtained in ATLAS). CMS has recently provided a first determination of the b -jet energy correction using $Z + b$ events [21] with a precision of around 0.5%, being compatible with unity (see Figure 1).

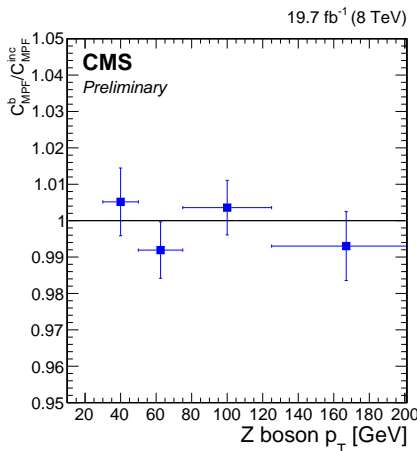


Figure 1. Energy correction for b -jets as a function of the Z boson p_T obtained as the ratio of the b -tagged and inclusive jet energy corrections in $Z + b$ events [21].

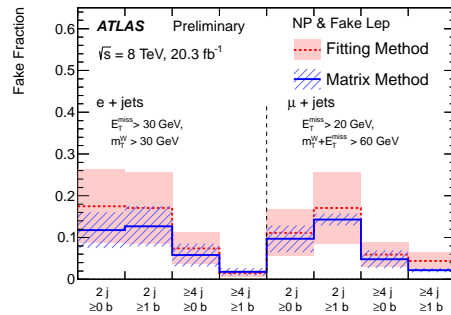


Figure 2. Comparison of the non-prompt and fake lepton background predictions by the matrix method and the fit method divided by the number of observed events in each of the lepton+jets signal regions [13].

The detail comparison of the procedures followed in both experiments has led to the recommended categorisation of the jet energy scale uncertainty components and ATLAS/CMS correlations documented in [22].

For what concerns the jet calibration procedure followed at the Tevatron experiments [23, 24], the main differences with respect to the LHC strategy are the following: CDF corrects the jet energy to parton level rather than to particle level. D0 does calibrate the jets to particle level but applies an also called absolute calibration in the sense that the same calibration procedure is applied to both data and MC. Both Tevatron experiments do also correct for the underlying

event while this is not the case at the LHC. The D0 experiment has recently provided a new calibration in which dedicated corrections are applied to light, b and gluon jets [24].

3. b -tagging

The four experiments have developed various algorithms to identify b -jets. Those mostly employed in top quark analyses, use the fact that due to the long lifetime of B -hadrons, tracks with large impact parameters as well as displaced vertices can be found. This kind of information is combined in different ways in the b -tagging algorithms used by default in the different experiments. For instance, CMS uses a likelihood approach in the CSV tagger [25], while ATLAS and D0 use a neural network in the MV1 [26] and MVA [27] algorithms, respectively, to provide a discriminant.

It is essential to check at which level the simulation predicts the shapes of the discriminants used in the taggers and, if needed, correct the simulation via data/MC scale factors. The calibration consists then in measuring the efficiency in data and MC. A detail comparison of the b -tagging calibration strategy used in ATLAS and CMS has recently been performed. The general idea is to select a sample enriched in b -jets and then compute the content of b -jets before and after applying the b -tagging requirement. One possibility is then to use a sample of jets containing muons, which is an independent sample to that used in a top quark analyses. However, the question is whether the obtained scale factors are also applicable to inclusive b -jets, and ATLAS and CMS do take different approaches in this respect. In ATLAS, the difference between the scale factors obtained for the case of jets containing and not containing muons in $t\bar{t}$ events is measured and found to be compatible within an uncertainty of 4%. This uncertainty is then considered as an additional source of systematic uncertainty, which results as being the dominant source, not being considered in CMS on the other hand.

Another possibility to get a sample enriched in b -jets is to use $t\bar{t}$ events. Measurements have been performed in leptonic decay channels using various techniques and reaching a precision of $\sim 2\%$ for jets of p_T around 100 GeV, which is significantly better than that achieved when using an inclusive sample of jets containing muons. However, when using this calibration in top quark measurements one should take into account that the scale factors are obtained assuming $V_{tb} = 1$ and that their associated systematic sources are largely in common to those affecting the top quark measurement under consideration, meaning that correlations should be treated correctly.

In both experiments, a good agreement between the top quark pair based and muon jet based calibrations is found, and therefore various combinations of the measured scale factors are provided. For each uncertainty source, the size as well as the strategy followed to estimate it in each experiment has been compared. For the purpose of combinations, it is then recommended to provide six different components of the b -tagging efficiency related uncertainties, as documented in [28], one of them to be treated as uncorrelated and the others (stemming from modelling uncertainties) as fully correlated between experiments.

4. Non-prompt and fake lepton background

Among the various methods used to estimate the non-prompt and fake lepton backgrounds in top quark analyses, the most commonly used are the following two, which have been studied in detail in [13] for the case of the data collected at $\sqrt{s} = 8$ TeV during 2012:

- **Matrix method:** It is based on the measurement of the lepton efficiencies for leptons with relaxed identification criteria to pass the requirements used in the analysis. The real lepton efficiencies are measured using Z boson decaying to electron or muon pairs using a tag and probe technique. For the case of electrons, an additional correction is needed to account for efficiency differences in top quark and Z events. The fake efficiencies are measured from control regions enriched in fakes, subtracting the real lepton contribution as estimated

from simulation. The efficiencies are measured as a function of various variables, chosen based on the actual dependence observed, agreement in the control regions and ensuring a small correlation between them. Systematic uncertainties, evaluated by changing the just mentioned parametrisation, using different control regions and varying the contribution of real leptons in the fake control region, range from 10-50% (30-50%) for the one lepton (two lepton) final states.

- **Fitting method:** It consists on defining a model to predict the shape of the non-prompt and fake lepton background for a given distribution (as for instance the transverse missing energy). Using templates for the other processes derived from simulation, a likelihood fit to data is then performed to extract the normalisation of the non-prompt and fake lepton background. Systematic uncertainties are then evaluated by using different variables in the fit, varying the fit constraints, and from uncertainties in the modelling of W/Z +jets, leading to an overall uncertainty of 50% in the one lepton channel.

The predictions given by the two methods have been compared and found to agree within uncertainties, as shown in Figure 2.

5. Summary

The exploitation of the full data set collected by the LHC (and previously Tevatron) experiments have led to significant improvements on the uncertainties associated to the objects appearing in top quark final states. Recent progress also took place at the LHC in comparing the strategies used in ATLAS and CMS for the jet energy scale and b -tagging calibrations leading to concrete recommendations on how to treat these uncertainties in the context of LHC combinations.

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